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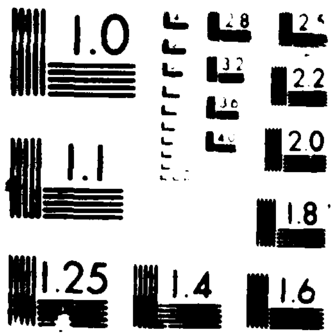
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This report covers research performed under Grant AFOSR-85-0288. The work consisted of six separate projects:

1. Rotor Dynamic Instability due to Alford Forces
2. Turbocharger Stall
3. Three-Dimensional Flows in Turbomachines
4. Computational Techniques for Turbomachine Flows
5. Active Stabilization of Surge
6. Fluid Physics of High Pressure Ratio Turbines

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PERIOD OF INVESTIGATION: 9/1/86 - 8/31/87

December 1987

Introduction

This is a progress report for the research conducted under AFOSR Grant AFOSR-85-0288, Air Force Research in Aero Propulsion Technology (AFRAPT). The research was conducted in the Gas Turbine Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology. The AFRAPT trainees, supervisors and the different projects and sources of support are as follows:

Trainee: Steven Allmaras
Advisor: Prof. M.B. Giles
Project: Computation Techniques for Turbomachines (Unsteady Flows in Turbomachinery) (AFOSR)

Trainee: Louis Cattafesta
Advisor: Prof. A.H. Epstein
Project: Fluid Physics of High Pressure Ratio Turbines (Rolls-Royce Inc.)

Trainee: David Fink
Advisor: Prof. E.M. Greitzer
Project: Turbocharger Stall (Cummins Engine Company)

Trainee: Knox Millsaps
Advisor: Prof. M. Martinez-Sanchez
Project: Rotor Dynamic Instability Due to Alford Forces (NASA MSFC)

Trainee: Judith Pinsley
Advisor: Prof. E.M. Greitzer
Project: Smart Engines - Active Stabilization of Aeromechanical Systems (Army Aeropropulsion Laboratory)

Trainee: Earl Renaud
Advisor: Dr. C.S. Tan
Project: Three-Dimensional Vortical Flows in Axial Turbines (NASA LeRC)

Descriptions of the Research

Brief descriptions of the different research projects are given below; detailed descriptions will be given in the M.S. and Ph.D. theses of the graduate student trainees.

Computation Techniques for Turbomachines (Unsteady Flows in Turbomachinery)

Steven Allmaras has been in the AFRAPT program since September 1986. He is currently a Ph.D. candidate working with Prof. M. Giles and expects to finish his dissertation by August 1988. His current research is algorithm development for numerical simulation of unsteady 2-D shock/boundary layer interaction. Such interaction can be important in transonic inlet and diffuser geometries.

The research effort consists of two phases. The first is development of an unsteady Euler solver for the outer inviscid flow. The highlights of this explicit time-marching algorithm are crisp resolution of shocks through the use of flux-vector splitting and very low numerical error by maintaining second order accuracy regardless of grid smoothness. Low numerical error allows small amplitude acoustic waves to be correctly propagated without being dissipated. This phase of the research was completed by June 1987 and was presented in a paper at the AIAA 8th CFD Conference [1]. The attached figure is from that paper. It plots one period of the flow field for a transonic diffuser geometry driven by a sinusoidal exit pressure variation. As the figure shows, the pressure wave from the exit steepens into a shock as it travels upstream.

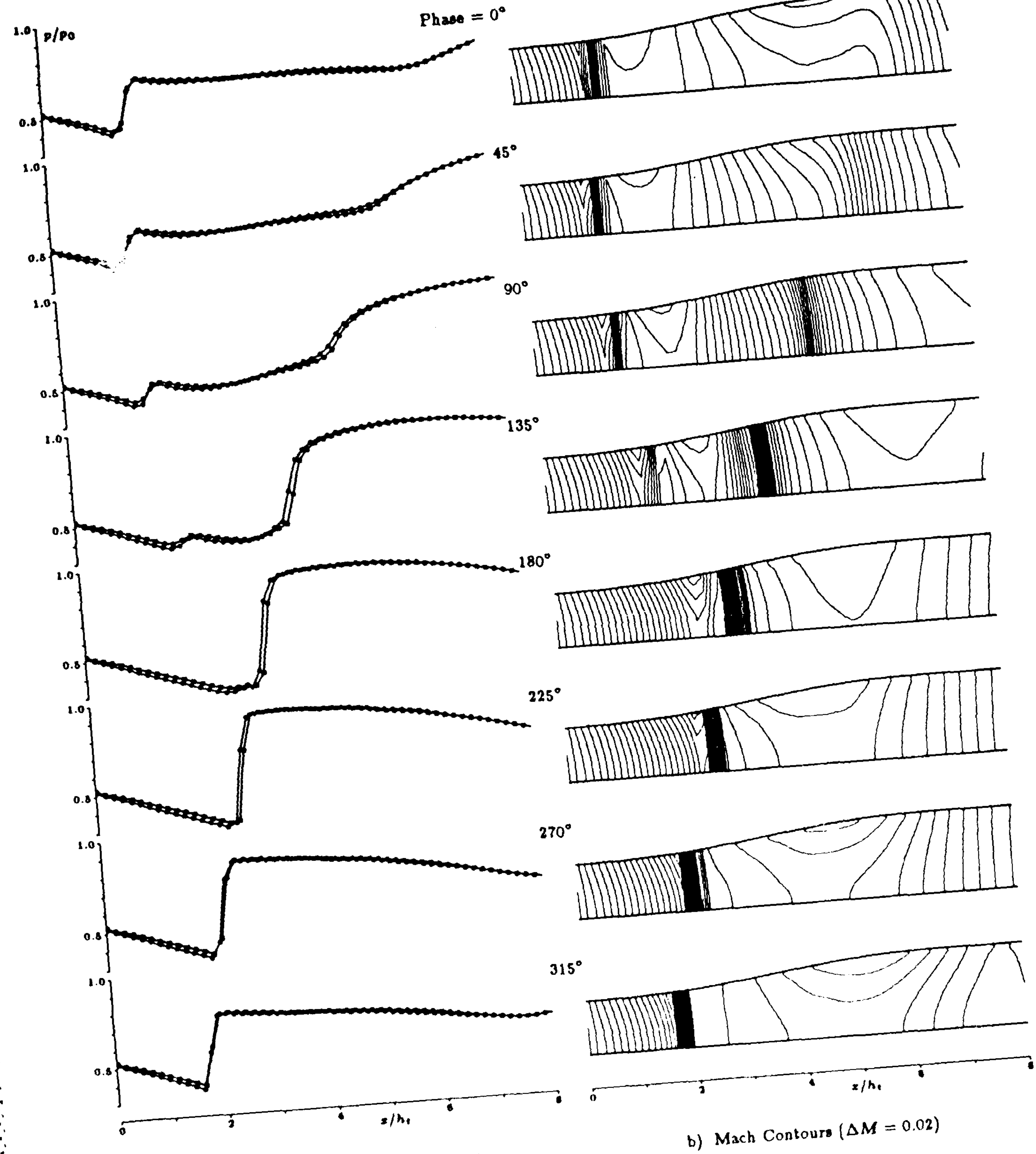
The second phase of the research is an extension of the current algorithm to unsteady Navier-Stokes simulations by inclusion of viscous and turbulence effects. Resolution of boundary layers requires very fine grids, which can result in excessive computational costs for an explicit algorithm. To reduce these costs, the algorithm will be modified to solve the equations implicitly across boundary layers while remaining explicit in the outer inviscid region. This phase of the research was begun in September 1987.

From June to August 1987, Mr. Allmaras worked with Pratt and Whitney

Aircraft in East Hartford, CT on algorithm development for numerical simulation of unsteady 3-D rotor/stator interaction, as part of the AFRAPT program.

Reference

1. Allmaras, S.R., and Giles, M.B., "A Second Order Flux Split Scheme for the Unsteady 2-D Euler Equations on Arbitrary Meshes," AIAA Paper 87-1119-CP, June 1987.



a) Lower and Upper Wall Pressures

b) Mach Contours ($\Delta M = 0.02$)

Figure 14: Diffuser Flow Variation due to a Sinusoidal Exit Pressure Excitation of 20% Amplitude and Reduced Frequency of 0.25 for a Mean Exit Pressure Ratio of 0.80

Fluid Physics of High Pressure Ratio Turbines

The majority of turbine aerodynamic studies have used uniform inlet temperature profiles to simplify the experimental analysis. However, a uniform profile does not accurately model the exit conditions of the combustor where large radial variations in temperature are present. Louis Cattafesta is carrying out an experimental investigation of the effects of radial temperature distributions on important aerodynamic parameters such as stage temperature and pressure ratios in the MIT Blowdown Turbine Facility. Concurrent with this research effort has been the development of total pressure and total temperature rakes to measure the inlet and exit conditions of the turbine stage.

The MIT Blowdown Tunnel is a short duration (0.4 sec) facility which is capable of testing a 0.5 meter, high-work, film-cooled aircraft turbine stage under conditions which simulate all the known important effects in turbine aerodynamics and heat transfer. In the last year, Mr. Cattafesta designed and constructed two total pressure rakes and two total temperature rakes to measure the inlet and exit conditions of the stage. All rakes consist of five probes placed at the centers of annuli of equal areas. The pressure transducers are the silicon wafer strain-gauge type, while the temperature transducers are Type K thermocouples (Figs. 1 and 2).

The design of the temperature probes is especially tricky because of the high order of accuracy (i.e. typically 1°F) required to report an adiabatic efficiency which is accurate to 0.5%. This is because the thermocouples must rise from room temperature to approximately 400°F in under 250 msec. To the best of our knowledge, no such probe has ever been built. Recent analyses by Mr. Cattafesta have shown that the major source of error in the temperature measurement is conduction of heat along the thermocouple stem to the probe body. Mr. Cattafeta has recently been experimenting with electrically heating

the body of the probe to a temperature which is close to that which the thermocouple will measure in order to reduce the temperature gradient (i.e. heat conduction) along the thermocouple stem. The result should be a substantially increased accuracy in the temperature measurements.

Future work includes calibration of the instrumentation, wind tunnel testing (scheduled for December and January), and analyses of the results. Mr. Cattafesta spent June to August at General Electric Company, Lynn, MA, working on particle separation for aircraft engine inlets. He expects to receive his S.M. degree in June of 1988.

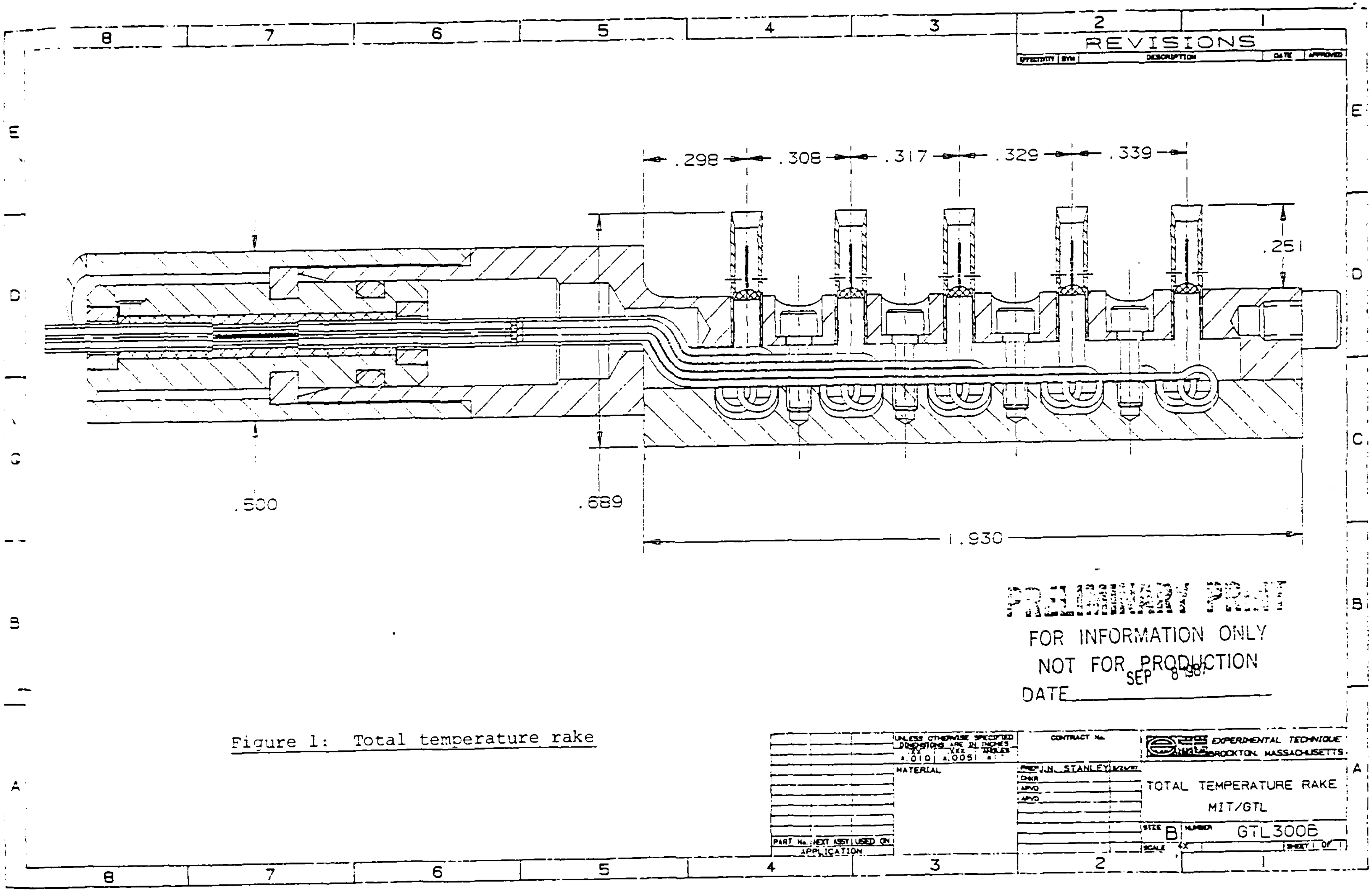


Figure 1: Total temperature rake

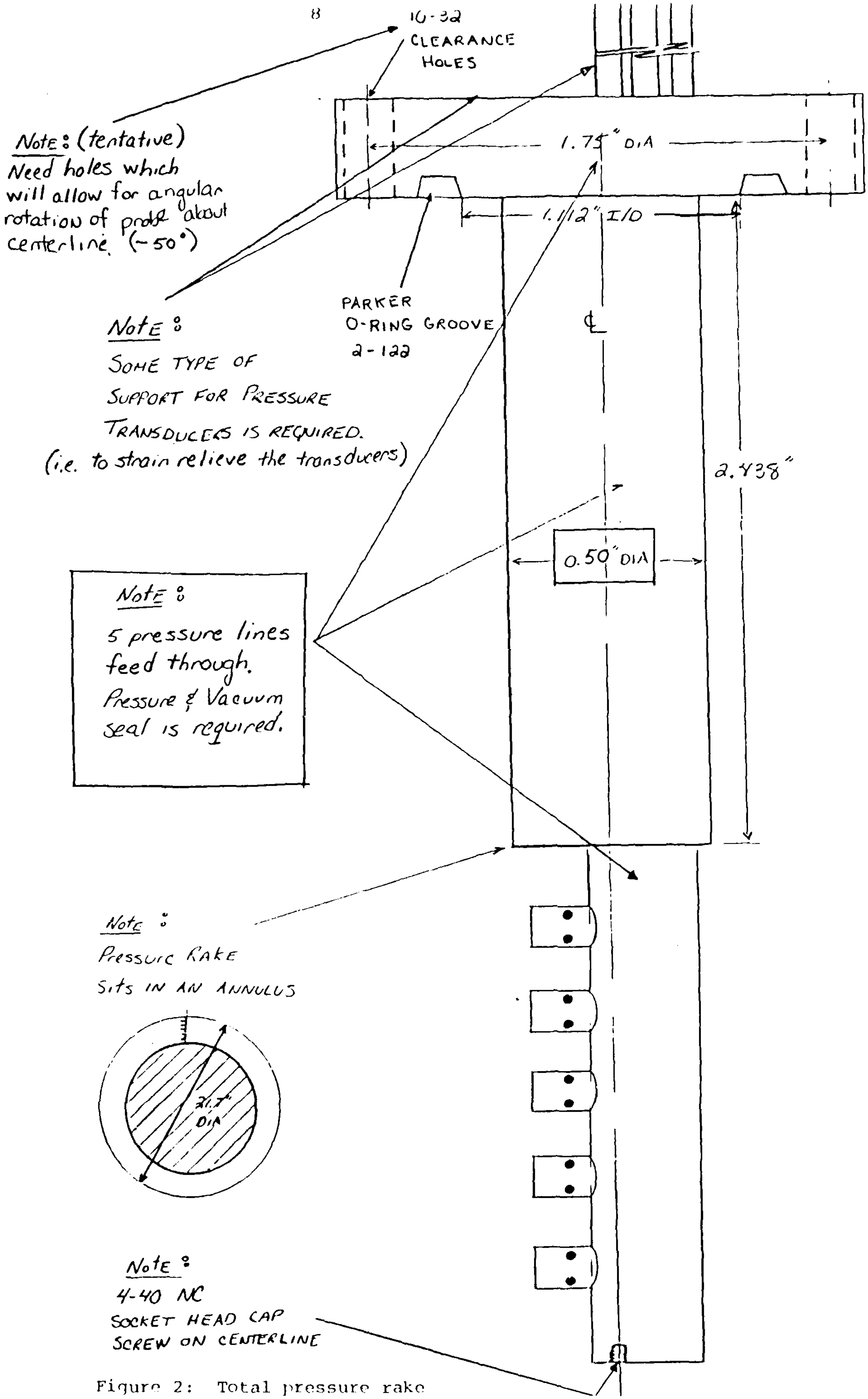


Figure 2: Total pressure rake

Turbocharger Stall

This project is an investigation of the fluid mechanic phenomena that characterize centrifugal compressor stall and instability. In particular, the aim is to isolate those parts of the process which are crucial to developing useful predictive modes of the unsteady behavior. The research is being carried out by David Fink.

Mr. Fink has completed his experiments and is in the final stages of writing his Ph.D. dissertation. The thrust of his experiments consisted of a detailed investigation of the behavior of the flow in the components of a centrifugal compressor (turbocharger) stage when the stage was operated in two quite different systems. One of these had a large downstream volume, and one had almost no volume downstream. Because of this (as can be seen from simple lumped parameter analyses), the former exhibits instability due to stall at a certain point in the operating regime. The latter configuration, however, is stable over a much wider flow range. It was thus possible to obtain measurements of the component performance down to lower flow than with the large volume, and this allows one to much more readily extract the important effects.

Among the central conclusions of Mr. Fink's research are the clear demonstration that it is the performance of the vaneless diffuser which is the root cause of the instability. In addition, it appears one can explain the instability using a rather simple fluid dynamic model; this is of interest since esoteric explanations have been proposed in the past for the sequences of events that characterize the surge. One further byproduct of the experiments is the implication that the growth of the instability is slow enough, and the frequencies are low enough so that active control of compressor instability (which we are pursuing under another AFOSR contract) seems to be quite feasible.

Rotor Dynamic Instability Due to Alford Forces

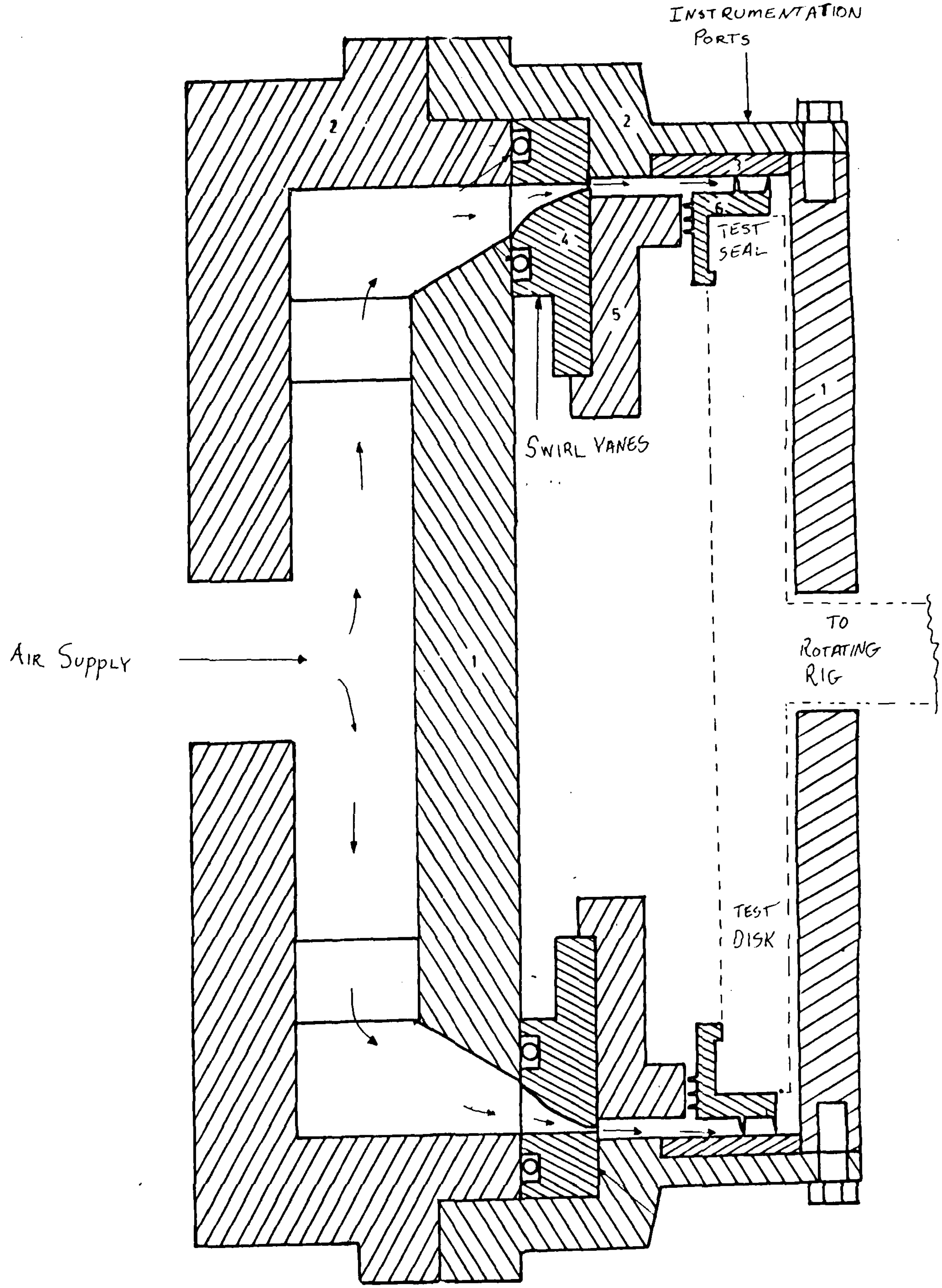
Knox Millsaps has been investigating the destabilizing [illegible] from the non-uniform clearance flows generated in labyrinth seals [illegible] work is part of a broader effort to understand and predict the [illegible] working fluid flow on the dynamic stability of high power density turbomachinery. Such machinery is found in the pumps of the space shuttle main engines. In the past year, both analytical and experimental work has been performed.

Analytical Work

In previous years, the analytical work was directed towards obtaining very simple lumped parameter models. Elementary linear approximation techniques were employed in the solution of the resulting equations. The preliminary results, based on these analyses, were needed in order to properly design the complementary experimental facility. The analytical work conducted over the past year has attempted to improve and extend earlier models. Also, more advanced mathematical methods have been brought to bear on the resulting equations. Certain physical phenomena which were not observed in the linear case, such as relaxation oscillations, may be important under special conditions. Future work will continue along these lines.

Experimental Work

In order to test the dynamic characteristics of labyrinth seals, an air supply/test section was designed and is now being fabricated. Figure 1 shows a cross-section of the test section. The seal, part 6, is driven in a precisely controlled manner with air blowing through as shown. Instrumentation, attached to part 3, monitors the aerodynamic conditions inside the gland of the seal. The acquisition and development of this instrumentation and the associated software for data acquisition/reduction has been proceeding throughout the year. Facility shakedown and baseline calibration should begin early next year.


INSTRUMENTATION PORTS
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TEST SEAL
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SWIRL VANES
TO ROTATING RIG
AIR SUPPLY
1
TEST DISK

Smart Engines - Active Stabilization of Aeromechanical Systems

Compressor surge is a severe, low frequency global instability which occurs when the compressor is operated below its stall point. Judith Pinsley is carrying out an experiment on active surge control. The basic concept is to suppress potentially damaging surge cycles in a centrifugal compressor by means of a control feedback scheme. Analyses performed prior to the experiment indicated that a variable throttle area controller could effectively prevent surge and extend the compressor's operating range. The controller itself would require very little power in comparison to the power requirements of the compressor.

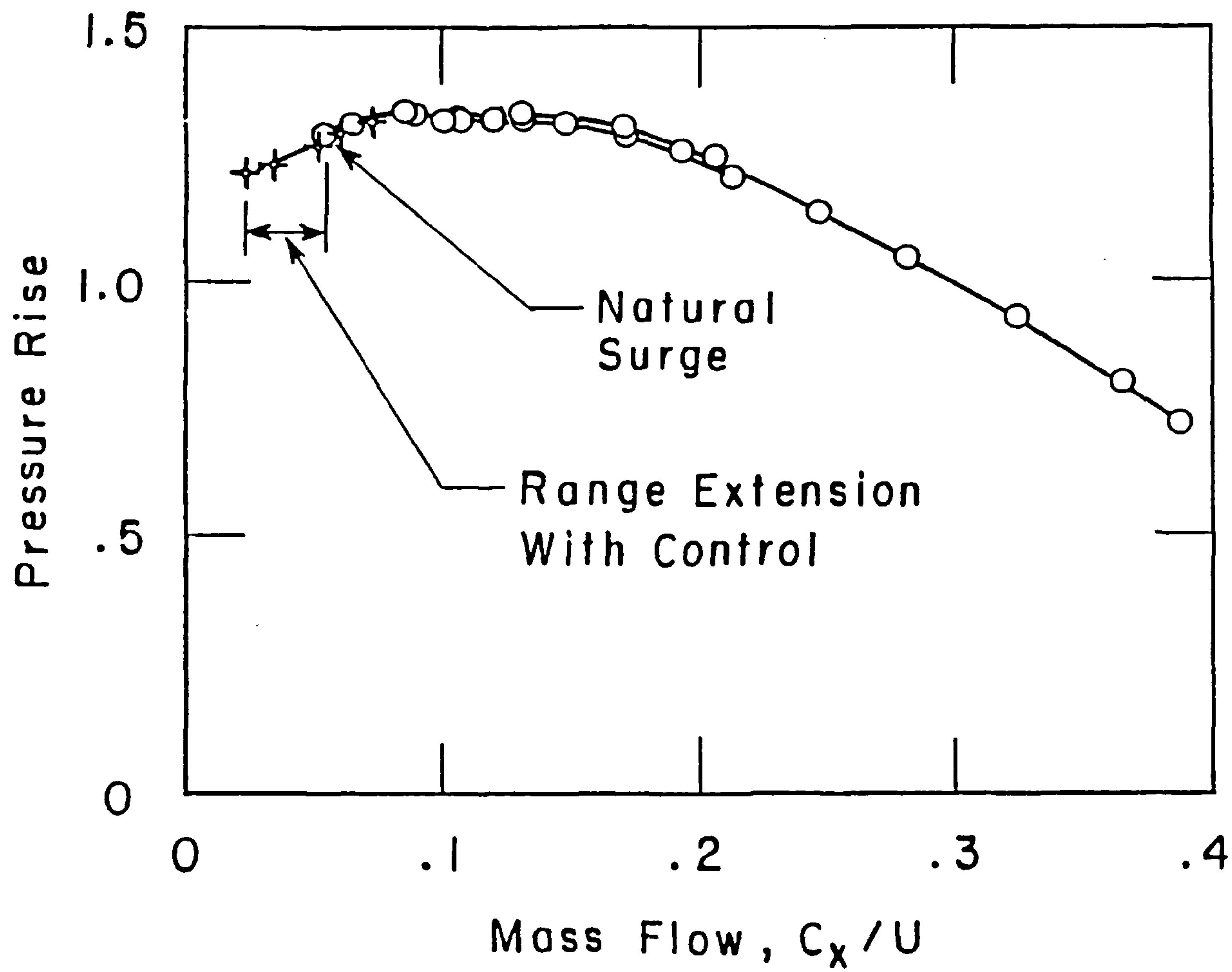
The first experimental project was a small-scale test rig designed as a proof of concept. A truck turbocharger discharging to a plenum with a moveable gate throttle comprised the major test section. The data was taken at low turbocharger speeds, such that a loudspeaker could drive the moving gate as the control input. The loudspeaker itself was driven by pressure fluctuations in the plenum. The controller was able to extend the stable operating range below the natural surge point and, on a nondimensionalized plot of plenum pressure rise versus mass flow, the mass flow at surge with the controller on was over 50% lower than the natural surge point. In addition, the controller was able to induce surge before the natural instability point, as predicted by analysis.

Once the controller was proven effective at low speed, the decision was made to scale the test rig to operate near the higher turbocharger design speed. The surge point occurs at higher mass flows there, so the available control range would be larger. The extreme conditions associated with high speed operation entailed a complete redesign of the rig in size and material. The simple loudspeaker-driven gate valve was replaced by a motor-driven rotary

valve.

To date, the new rig has been built and the instrumentation is in place for an automated data acquisition system. The rotary valve, which is an in-house design, is being fabricated with a target completion date of mid-December. High speed tests will commence upon valve installation.

PRELIMINARY ACTIVE CENTRIFUGAL COMPRESSOR TEST RESULTS
Low Speed (30,000/120,000 RPM)



Three-Dimensional Vortical Flows in Axial Turbines

The flow through the rotors of axial flow turbines is inherently unsteady due to the periodic ingestion of upstream vane wakes. These circumferential distortions in the rotor inlet flowfield lead to periodic temporal variations in the basic rotor flow parameters, and hence, to temporal variations in the rotor passage performance. Earl Renaud has been studying how these circumferential distortions in turbine rotor inlet flowfields affect the secondary flow structure and associated total pressure loss within rotor passages.

Recent experimental investigations at the United Technologies Research Center suggest that large variations in the strength and structure of the secondary flow vortices occur as a turbine rotor passage ingests wakes from upstream airfoils. Analysis has revealed that the unsteadiness in vortex strength is exactly tied to upstream vane passing frequency, indicating that the ingestion of the vane wakes is in some manner affecting the formation of the normal secondary flow vortex system. Since these vortices account for a significant percentage of the total pressure loss within a blade row, changes in their strength and structure may have large effects on overall turbine stage performance.

To investigate this interaction between blade rows, a numeric simulation of the flow through a turbine rotor passage will be used to gain understanding of how vane wake ingestion can affect secondary flow vortex formation. Such a simulation must be able to predict the inherent three-dimensional nature of a streamwise vortex and be able to accurately assess the magnitude of the total pressure loss associated with such a vortex. Hence the scheme used should be a three-dimensional formulation with a minimum of numeric dissipation. For these reasons, a three-dimensional spectral element Navier-Stokes program developed by Dr. Choon Tan is being modified for use in this investigation.

The simulation will be used to study how the position and strength of upstream vane wakes affect the formation of the normal secondary flow vortices in a turbine rotor. After obtaining a baseline simulation using a uniform flowfield upstream boundary condition, a circumferential distortion representative of an upstream vane wake will be added to the inlet flowfield. A number of simulations will then be run varying the strength and circumferential location of this upstream distortion. This will give detailed information about the interaction of upstream vane wakes and the secondary flow vortex sytem.

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